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Active Control of Complex Physical Systems: An Overview

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ABSTRACT

Active control of complex systems imposes unique requirements for physical models and feedback control strategies. Physical models which are adequate to predict the influence of actuators must be coupled with feedback control approaches suitable for use when system characteristics are incompletely specified *a priori* and change with time. The present paper describes laboratory scale experiments in which turbomachinery surge and stall and combustion instabilities are successfully attenuated by active means. Work which has been conducted in parallel to develop improved models and control strategies to realize fault tolerant active control of such systems in the full scale operational environment is also discussed.

INTRODUCTION

During the first half of the decade of the 80s substantial progress was realized in actively controlling simple physical systems. Examples included attenuation of low frequency sound in air and liquid filled ducts (1) and vibration in a variety of simple structures. These simple systems could be described by ordinary differential equations, and required the use of only one or a small number of active elements. These early successes led to speculation that active control concepts might be applied to more complex systems and processes, such as rotating stall in axial flow compressors (2).

In 1987 the Office of Naval Research (ONR) initiated a program to establish the limits of utility of active control concepts in complex systems, governed by partial differential equations and requiring a multiplicity of sensors and actuators for control. Physical systems and processes were selected for study which are both of practical importance and, when taken together, embody the major problems expected to be encountered in applications of active control concepts. They included sound and electromagnetic energy radiation, turbomachinery surge and stall, and combustion instabilities and processes.

This work on the active control of specific physical systems has been coupled with the development of improved fault detection and adaptive feedback control methodologies. Emphasis has been given to the application of adaptive algorithms to the active control of multivariable, distributed parameter systems (3) particularly where the plant model is incompletely specified *a priori* or changes with time. Approaches based on postmodern control theory and applied artificial intelligence have been utilized.

In the present paper progress made to date in actively controlling turbomachinery instabilities and combustion and in developing improved fault detection and feedback control strategies is described. Both combustion control and improved fault detection and control methods are potentially relevant for the development of improved gas turbine engines. Combustion control may prove beneficial in advanced afterburner and combustor designs. Fault detection and feedback control algorithms may be applicable to the difficult control problems encountered in current gas turbine engines as well as in future systems which integrate flight and engine control and/or actively attenuate surge and stall.

ACTIVE CONTROL OF SURGE AND STALL

Within the program supported by ONR, three complimentary investigations have been carried out in parallel by Topexpress, Ltd. (Professor J. E. Ffowcs Williams), Georgia Institute of Technology (Professor C. N. Nett), and MIT (Professors Epstein, Greitzer and Valavani). The first has focused on surge control in an engine with a centrifugal compressor, the second on an alternate surge control approach and improved engine models and the third on rotating stall control.

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Topexpress identified a rugged laboratory scale (60 hp) turbine engine that can be taken into and out of surge without permanent damage. It was instrumented with flush mounted pressure sensors at selected axial and aximuthal locations within the engine and also equipped with an active control system for introducing small amounts of compressed air into the combustor with amplitude and phase determined by a controller. In experimental studies conducted with this engine with the controller off, highly nonlinear regimes of operation were identified, including classical limit cycle and chaotic behavior. These observations were consistent with the predictions of a relatively simple one-dimensional, coupled model of the compressor, combustor and turbine. With the control system on, the experiments showed that surge could be attenuated within a single surge cycle and the limits of stable operation of the machine extended. Figure 1 shows the actual temporal record from a pressure sensor just downstream of the compressor with the controller off and the controller on as the engine is taken into surge. This result is particularly noteworthy in that blowing, used here for stabilization, is generally a destabilizing influence to fluid dynamic phenomena. Additional details of this work are given in reference 4.

The work currently in progress at Topexpress has two thrusts. The first is to develop an improved controller to further attenuate surge. The second is to develop an improved model for the noisy environment represented by the interior of a turbomachine for incorporation into future modeling and control design work.

At Georgia Institute of Technology, two unique experimental facilities are now operational for active control studies. The first is a laboratory scale engine with a centrifugal flow compressor. Active control of surge is exercised by temporally varying suction from the combustion chamber. Preliminary experiments have shown that, with this configuration, the engine may be taken into a surge regime without the appearance of even a single surge cycle. The second facility is a two stage axial flow turbine in which each stage is driven by an independent electric motor. By varying the relative speed of the stages a rich variety of instability conditions may be achieved, corresponding to a broad range of compressor designs. When this facility is fully characterized, it will be used to conduct experimental studies of active surge control and stall avoidance over this broad range of conditions. These experiments have been complemented by the development of a compressible flow version of a stall-capable model of a turbine engine. More detailed information on this work is given in reference 5.

The MIT effort has focused on the identification of a precursor for and active control of rotating stall by azimuthally distributed sensors and actuators. This work is described in detail in a recent Ph.D. dissertation (reference 6). A single-stage low speed compressor was instrumented with eight azimutally distributed hot film anemometers to measure flow velocity upstream of the inlet guide vanes. When the outputs of these sensors were processed as a wavevector filter, the output phase of the array gave a clear precursor to rotating stall.

TURBINE ENGINE SURGE

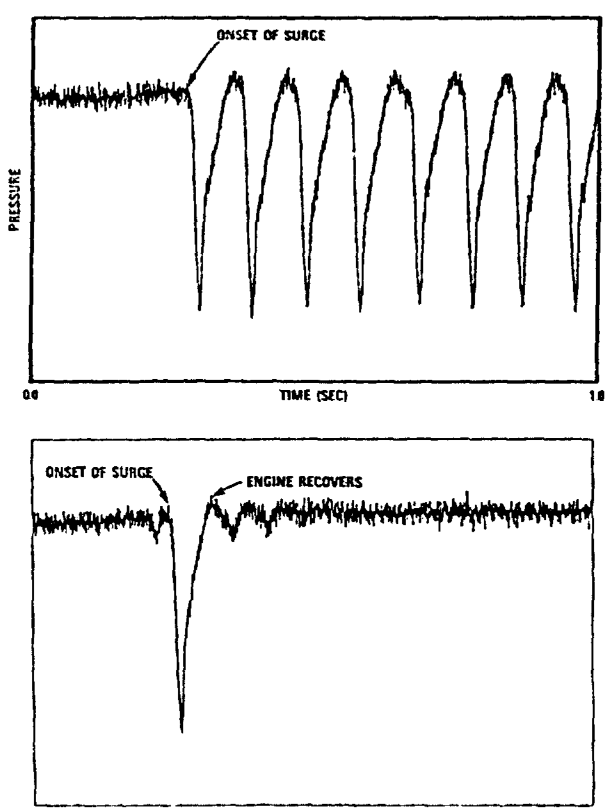

Figure 1: Pressure flucations in a laboratory scale engine as it is taken into surge: (a) controller off; (b) controller on.

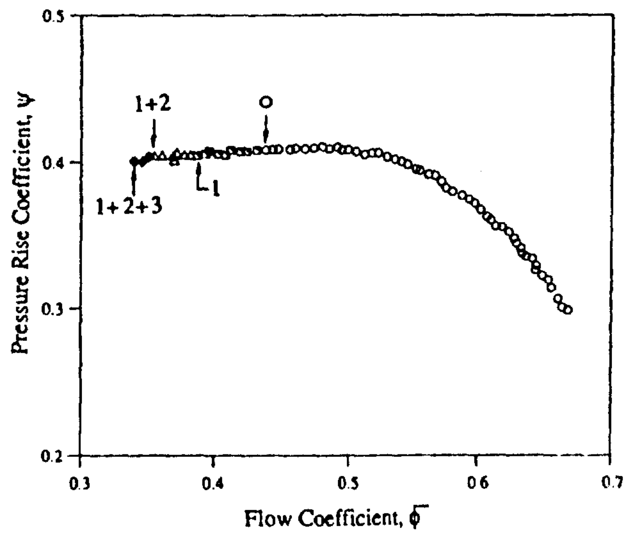

Figure 2: Extension of the range of stable operation of a low speed, axial flow compressor by active control (0=no control; 1=control of the first azimuthal mode, 1+2=control of azimuthal modes 1 and 2; 1+2+3=control of the first three azimuthal modes).

(Subsequently, similar results were observed with flush mounted pressure probes in larger compressors.) The low speed compressor was also equipped with twelve independently moveable inlet guide vanes, and a control system was developed to use the hot film inputs to move these active elements in such a way as to attenuate rotating stall. Results obtained to date are shown in Figure 2. If the plant model is based on the supposition that rotating stall consists of one azimuthal mode, modest improvement in the stall margin is observed. As a more realistic (i.e., higher number of mode) model is incorporated, the stall margin becomes progressively larger, with a three mode model extending the range of stable operation of the compressor to a flow coefficient 23% below its value with no control.

Taken together the results of these investigations demonstrate that active control of surge and stall can be achieved at laboratory scale. They suggest that active control concepts may be employed to improve the performance of current engine designs and, perhaps even more important, give flexibility in the design of future engines to achieve improved performance over board operational envelopes.

ACTIVE COMBUSTION CONTROL

The focus of the combustion control component of the ONR program has been the suppression of combustion/pressure oscillations and the extension of flammability limits in ramjets and afterburners. The overall approach taken has been to apply a physical understanding of the combustion processes in combination with appropriate control theory, sensors and actuators. Experiments in flames and laboratory combustors using advanced diagnostics are being conducted in order to provide insight into the interaction between the reacting shear layers and duct acoustics during active control. Physical understanding of combustion phenomena has also been enhanced by utilizing numerical large-eddy simulations (LES). LES calculations have demonstrated the effectiveness of several active control techniques on combustion/pressure oscillations. The control strategies explored in small-scale laboratory experiments and numerical simulations are being applied to improve the performance of larger scale laboratory combustors.

A common element of all of the research efforts in progress is the ability to actively manipulate the initial shear layer instability at the flameholder to disrupt the development of large-scale coherent structures. (These vortical structures have been shown to drive combustion instabilities and to play a critical role in the flameholding process.) Passive methods have been developed which partially perform this function over limited parameter ranges (7). Active control provides a method for enhancing these results and extending them to broad parameter ranges (operating envelopes.)

Experiments at high energy levels in ramjet combustors show the nonlinear behavior of the combustion dynamics. The nonlinear character of the processes has made modeling difficult. At the California Institute of Technology an approximate analysis has been used to characterize the combustion behavior (8). This analysis predicts the linear behavior of combustion at low energy levels in quantitative agreement with observation in laboratory devices and suggests that both nonlinear gas dynamic and nonlinear combustion processes must be considered to explain the high energy measurements. Additional work is currently in progress to determine if there exists stable limit cycles and whether any bifurcations occur in the nonlinear acoustics of combustion. Utilizing a time delay embedding technique developed for nonlinear systems analysis (9), the Cal Tech investigators have observed preliminary evidence of a low-dimensional attractor in the laboratory combustor data. Figure 3 is a plot of the slope of correlation dimension, C(r), of the pressure oscillations as a function of scale, r. (The temporal signal consists of 8150 points at 80 microsecond intervals, embedded in a nine - dimensional space using a 400 microsecond time delay). The ordinate of this plot is a measure of the dimension of the attractor traced out by the data in phase space. An approximately a two-dimensional attractor can be observed over an order of magnitude of r in this plot, suggesting that the observed combustion oscillations are a low order dynamical system. It is unclear at this time if this behavior may be associated primarily with nonlinear gas dynamics or combustion processes.

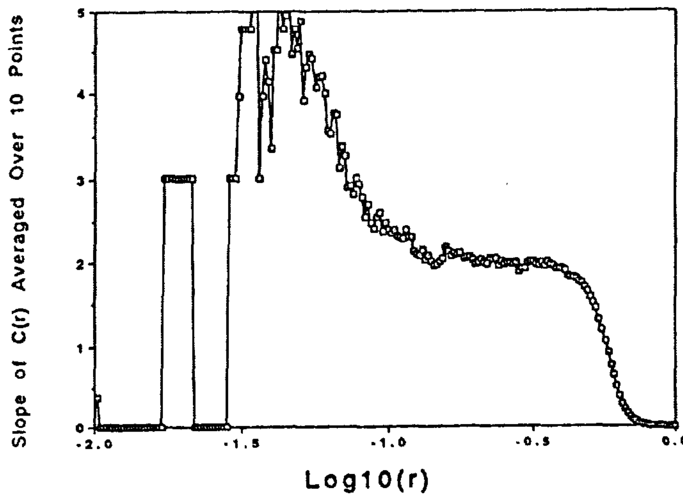

Figure 3: Correlation dimension C(r), of the experimentally measured pressure oscillation as a function of scale.

At Stanford University control of a subsonic dump combustor is exercised to enhance the volumetric energy release while sup-pressing combustion instabilities. The combustor has a test section which is rectangular (6 cm x 10 cm) and is fueled with premixed ethylene and air. Two novel actuators are being studied for effectiveness. The first is a streamwise vortex generator consisting of steady jets with controllable magnitude and the second a spanwise vorticity

generator which is a slot with controllable air flow. The feedback sensors being used are a pressure transducer to measure the combustion instabilities and photomultiplier tube with a narrow band filter (to sense C-H radicals) for the determination of volumetric energy release (10). At present, experiments are in progress to measure system response to the actuators. The data is employed to train a neural network for use as an optimal adaptive controller with a cost function relating to pressure fluctuations or energy release.

Researchers at the Imperial College of Science, Technology and Medicine are working to actively control the rough combustion regime of disk-stabilized flames with and without sudden expansions. They are utilizing oscillations of the pressure field (loudspeaker, vibrating diaphragm) and secondary fuel supply to control the instabilities. This group has successfully controlled the oscillations in their combustor for heat release rates of 50 to 100kW with rms pressures up to 4kPa using a pressure sensor feedback to knowledge based and adaptive controllers (11).

At Quest, Inc. a Large Eddy Simulation model of a dump combustor is being used to investigate the effects of active control on the dynamics of combustion. The simulations have identified two types of pressure instabilities. The type I instability is small amplitude (15% of mean pressure)-high frequency and the type II is a high amplitude (50% of the mean pressure)-low frequency disturbance. The simulations show extremely good agreement with data from real combustors. Additionally, the simulations demonstrate that both types of instabilities can be suppressed with closed loop feedback control and acoustic forcing (Figure 4), but that the oscillation

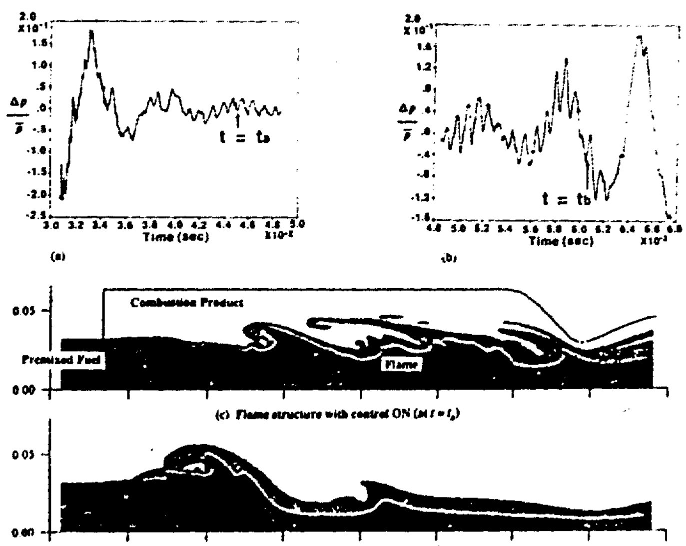

Figure 4: Large eddy simulation active control of pressure oscillations in a dump combustor: (a) control on; (b) control off; (c) flame structure with control on at T=t_a; (d) flame structure with control off at T=t_b.

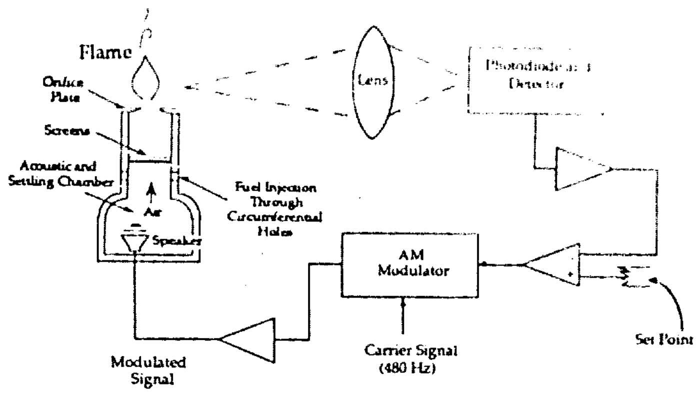

Figure 5: Schematic of ducted flame apparatus employed by NWC.

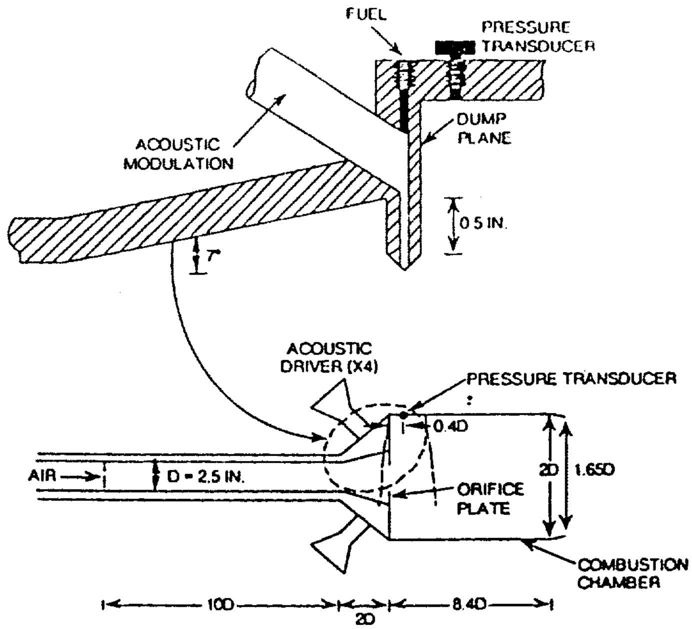

Figure 6: Schematic of 1 megawatt combustor employed by NWC.

of secondary fuel injection tends to excite the type II modes when control of the type I modes is attempted (12). Quest is currently doing simulations for the geometry of the large combustor being used at Naval Weapons Center (NWC), and the two efforts are closely linked.

At NWC experimental efforts in active control are ongoing in two facilities (13, 14, 15). NWC uses a ducted flame, (Figure 5) to do basic control investigations which guide experimental design for their larger 1 megawatt combustor (Figure 6.). NWC has used acoustic forcing to modify the shear layer of the flame and closed loop feedback and adaptive control coupled with a pressure or CH feedback to suppress combustion oscillations by 30 dB. Because of the much higher energy release in the larger combustor, a modulation of the fuel injected at the dump step was chosen as the actuation methodology. Using this approach pressure oscillations have been cut in half and lean flammability limits have been extended from .72 to .54 equivalence

ratio. Sample results are shown in Figure 7. This figure shows the evolution of the flow structure as manifested in CH emission images, CH emission levels at a single point in the flow, and pressure level in the combustor. The controller begins to drive pressure sources 0.26 msec before frame 2. The control system, which is a simple feedback control, is unable to handle multiple frequencies. Work is ongoing with the ducted flame to provide a neural net controller prototype which can be extended to the larger combustor, first with fuel flow modulation and subsequently with other actuator concepts if warranted. The neural network architecture employed is described below.

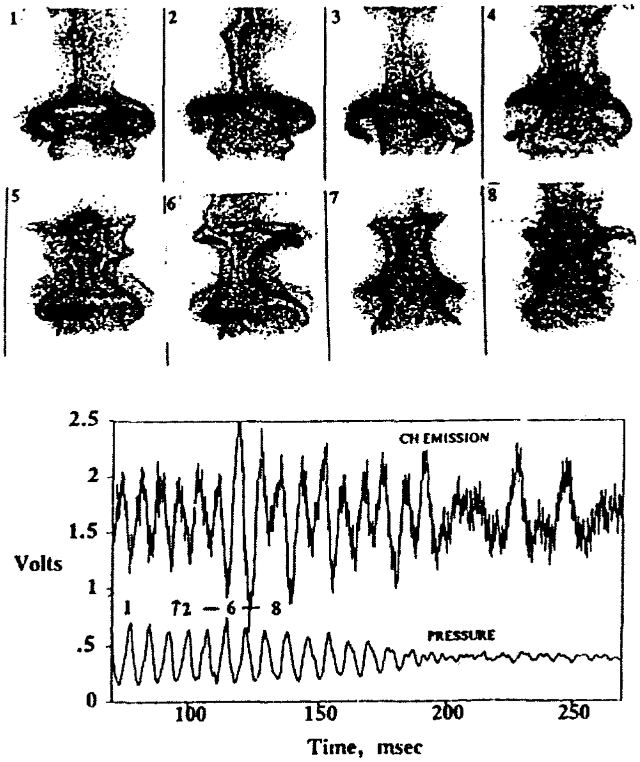

Figure 7: Time traces of pressure and CH and CH emission images of the transition from uncontrolled to pressure controlled flame control; (1) before control; (2) 0.26 msec after control turned on; (3) 1.9 msec after; (4) 6.2 msec after; (5) 15.3 msec after, (6) 17.5 after, (7) 28.5 msec after; (8) 37.9 msec after.

FEEDBACK CONTROL DEVELOPMENTS

The actual utilization of active control concepts in practical systems is critically dependent upon the development of fault tolerant adaptive feedback control strategies. Consider, for example, the use of active control to attenuate turbomachinery stall or surge, where a number of sensors and active elements are employed. The feedback control strategy must be able to accommodate incomplete specification of the system characteristics a priori, and temporal changes in these characteristics due to wear (gradual change) and component failures (sudden change.) More generally, control methods must be adequate not only for use in systems where instabilities are to be controlled, such as in turbomachinery, but also where field quantities, such as electromagnetic radiation, are to be altered.

Three promising methodologies which have emerged from the artificial intelligence community and now matured to the point of potential application for adaptive control have been investigated for achieving these goals in particular physical systems. They are dynamic polynomial neural networks, expert systems, and fuzzy logic. Results obtained to date with each are described below.

Dynamic Polynomial Neural Networks

The utility of neural networks for quasistatic problems such as pattern recognition is well established. Their suitability for the dynamic problems of system identification and control is less well known. In the present program, Barron Associates has been supported to develop and test network architectures which are suited to the dynamic environment. They have concentrated on networks whose elements have internal time delays and/or feedback loops. Additionally, they have developed network synthesis methods which employ information theory to constrain the number of network nodes to the minimum required for accurate system identification. A discussion of the concept of polynomial neural networks is given in reference 16.

One result suggesting the potential utility of this neural network formulation for system identification in feedback control relates to the range of parameters over which the network must be trained. A simple but important example is a nonlinear system described by May's population growth equation (17):

$$x(k+1) = Rx(k)[1-x(k)]$$

The time variation of the dependent variable $x(k)$ depends critically on the value of R, where k denotes the time step. This is shown in Figure 8 where $x(k)$ goes from a nearly constant value (R=2.75) to a limit cycle (R=3.50) to chaotic behavior (R>3.75). Suppose that the network is trained with data from $2.50 \leq R \leq 3.75$ and in a separate experiment with data from $2.50 \leq R \leq 3.25$. The mean square error of the network's prediction of future values of $x(k)$ in the two cases is also shown in Figure 8. Surprisingly, the network predicts the behavior of $x(k)$ in the chaotic domain even when not trained there. The implication is that the network can correctly predict behavior well outside the training range by correctly "learning" the underlying differential equation.

This finding needs to be investigated with progressively more complex systems because of its immense practical importance. Consider, for example, the problem of the system identification of a turbine engine. If we can train the network in stable domains and have it correctly predict performance in stall or surge domains where testing is difficult or impossible, a valuable addition to current system identification methods will have been gained. A similar statement applies to

characterization of combustion systems which are open-loop unstable over a part of their operating envelopes.

A second result suggesting the potential utility of the dynamic polynomial neural network architecture is its effectiveness for system identification of a combustion process. The combustion system is shown schematically in Figure 5. It consists of an acoustically modulated ducted flame which is monitored by a photodetector. Six data sets were available for analysis, two of 16.384 sec length and four 8.192 sec long. Figure 9a shows the comparison of the measured (solid line) and predicted (dotted line) photodetector outputs accomplished by a memory-feedforward network (internal time delays but no internal feedback loops.) The corresponding comparison using a memory-feedback network (internal time delays and feedback loops) is shown in Figure 9b. In both cases the AM excitation of the system is different from that used to identify the plant (train the network.)

Several conclusions can be drawn from these combustion studies. First, dynamic polynomial neural networks are effective for system identification of complex processes. The comparison of prediction with experiment shown in Figure 9 is quite good in light of the short length of the training data set. Second, a detailed analysis of the results shows that the memory-feedback polynomial neural network is superior to the memory-feed-forward architecture for this system identification problem. The mean square error of the estimates made with the former architecture is smaller than with the latter while using fewer coefficients to fit the data.

Presently the work on dynamic polynomial neural networks is being extended to the control of the Stanford and NWC combustion systems and to other complex systems, including a synchronous generator and a power distribution network. It would be desirable as well to incorporate such a network into a realistic turbine engine simulator to evaluate its effectiveness for identification and control of such a system.

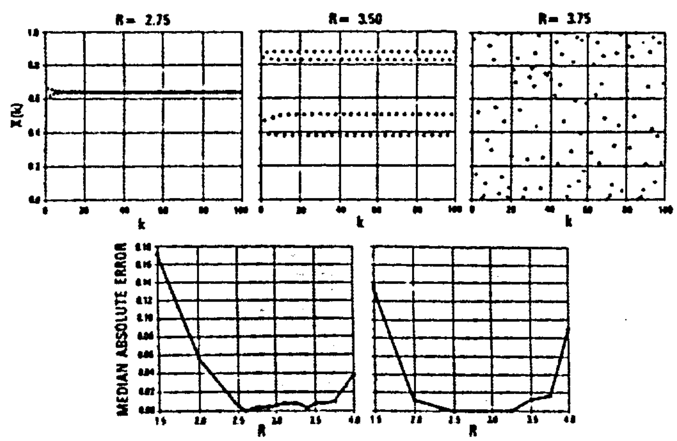

Figure 8: Dynamic polynomial neural network estimation of May's population growth equation: (a) time history of equation for R=2.75; (b) R=3.50; (c) R=3.75; (d) median absolute error of network estimate for a training range of 2.5≤R≤3.75; (e) median absolute error of network estimate for a training range of 2.5≤R≤3.25.

Expert System Based Control

While many of the promising potential applications of active control involve altering a perturbation quantity or instability phenomenon (e.g., turbomachinery surge and stall) still others require the control of a field quantity in a region. Examples include the control of optical, electromagnetic, and acoustic energy radiated from an object. The control of a reflected electromagnetic field, for example, has been treated by Bensoussan (18) and Lagnese (19) for cases in which the field may be controlled on the whole object boundary. The related problem of approximate controllability of Maxwell's equations, where control may be exercised on only a part of the surface, has been investigated as a part of the present

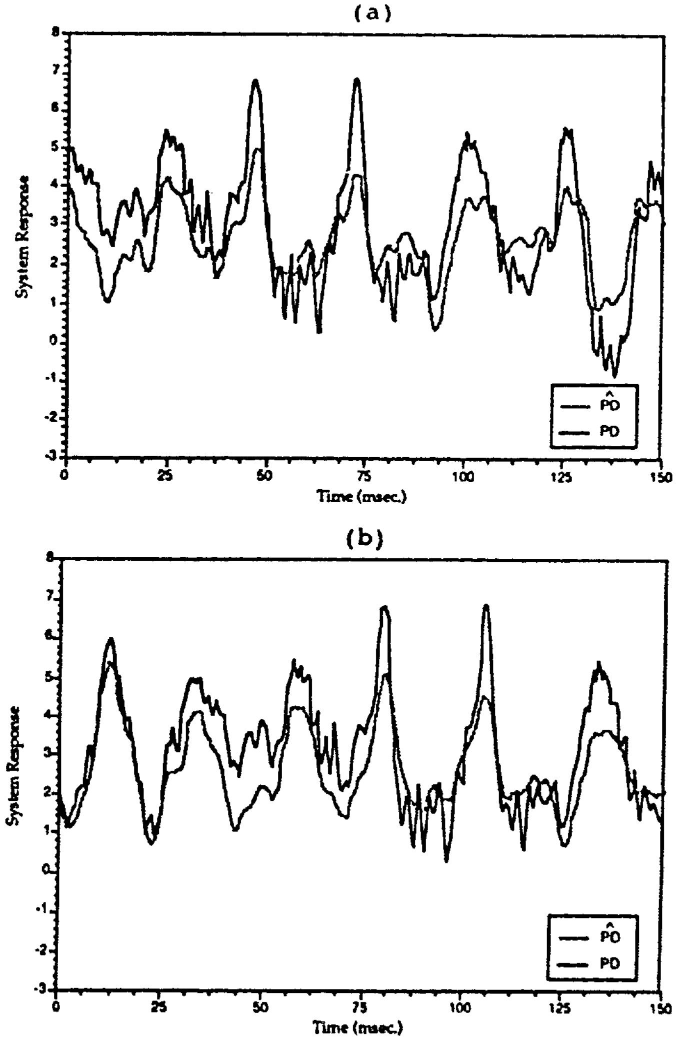

Figure 9: Dynamic polynomial neural network system identification of an acoustically modulated ducted flame (estimated and actual photodetector outputs vs. time): (a) memory feedforward architecture for a 150 msec time interval; (b) memory feedback architecture for an overlapping 150 msec time interval.

program. Specifically, Dr. Blankenship and associates have formulated this approximate field control problem on the basis of some of the consequences of Holmgren's theorem. They have also investigated the utility of an expert system-based feedback control method to drive active sources so that they locally cancel complex, a priori unknown incoming bursts of energy. The control system they have developed employs one node for each active element and internode communication and coordination. Each node consists of a PID controller, the coefficients of which are adjusted under the supervision of the expert system so as to minimize the local reflected energy in relation to the initially unknown incoming energy. It is anticipated that this adaptive architecture will be useful when some characteristics of the plant are known qualitatively, such as its functional form, but coefficients of the plant model must be continuously updated for optimal performance.

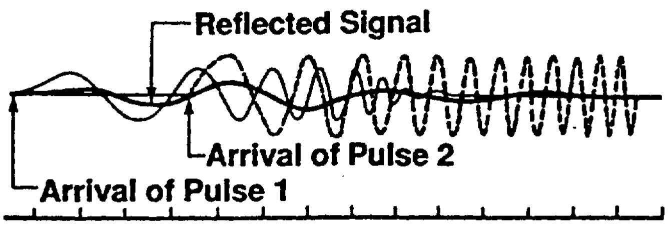

Figure 10: Initial reflected signal in response to two pulses of different starting and ending times, amplitudes, and center frequencies.

The results obtained to date with this feedback control strategy are very promising. Figure 10 and shows the time variation of the energy received by a sensor collocated with the active element and the initial active element response (i.e. before any adjustment by the expert system has occurred.) The energy being received is actually a sum of two chirp pulses with slightly different center frequencies, starting times, and durations. Moreover, there is a pulse-to-pulse variation in the center frequency and duration of each component of each pulse, with the same parameters being repeated every third pulse. (The first pulse is the same as the fourth, second as the fifth, etc.) The resulting composite temporal structure of each pulse is quite complex, and the structure of one pulse differs significantly from the next. Nevertheless, by the third pulse the energy reflected from the active elements is only a small fraction of that received, and by the sixth pulse the reflected energy is imperceptible. This behavior is shown quantitatively in Figure 11 where the net reflected signed (output) and the difference in the disturbance and control signal (error signal) are plotted as a function of pulse number at one active element.

While this distributed, expert system control strategy has been examined thus far in the context of Maxwell equation control, its uses may be much broader. It may in fact be generally useful for active control of systems where a multiplicity of active elements are required and the plant model is only partially

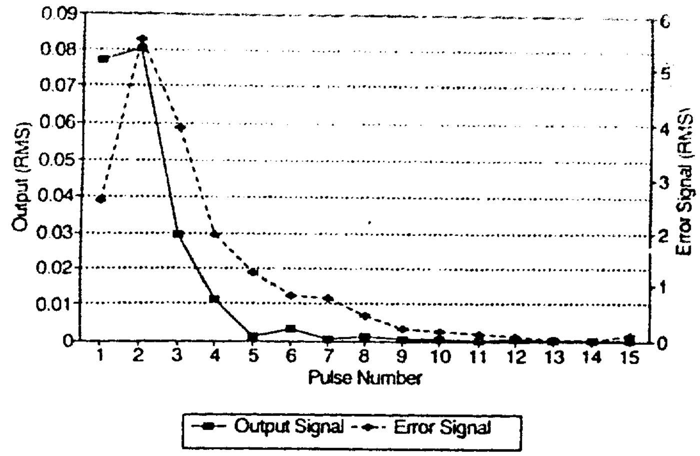

Figure 11: Reflected signal amplitude as a function of pulse number.

known a priori or changes in an unpredictable way with time due to wear, component failure, changing environmental parameters or other intrinsic or extrinsic factors.

Fuzzy Logic

The importance of detecting and identifying faults in any actively controlled system of practical utility motivated the examination of fuzzy logic based methodology proposed by Professor Vachtsevanos and his associates at Georgia Institute of Technology. This particular approach was selected because of its earlier successful applications to simple structures. Under ONR support the method was first extended to fault detection and identification in electric motor-controller combinations and subsequently to detection and classification of instabilities in an axial flow compressor.

The method employs a real time recursive parameter estimation algorithm with covariance resetting to track the value of the estimated parameter residue (the difference between the estimated and observed values) in the system and the time-averaged value of this quantity. When the residue exceeds a preset value, a fault may be present, so a histogram of the residue is constructed and converted to a fuzzy set. This set is compared to predetermined fuzzy set characteristics of system failure modes, to ascertain what failure mode has occurred. This comparison is analyzed on the basis of Dempster-Shafer theory (20) to also determine the certainty of this fault detection and identification.

The application of the methodology to detect and characterize present or impending instabilities of an axial flow compressor has been carried out using a nonlinear model (simulator) of the compressor dynamics (21). These instabilities/pending instabilities are treated as faults, each with a unique failure signature (fuzzy mode failure set.) The failure modes permissible in the simulator employed include potentially unstable operation, impending stall, rotating stall, impending surge, abrupt surge, and deep surge. Each is characterized by a particular relationship between rotor rotational speed, pressure drop across the compressor, and the

throttle area. One example is shown in Figure 12. The compressor experiences a start up transient as it goes from its initial state at time t=0 to its stable operating point at t approximately 0.5 sec. This transient corresponds to the smaller loop in the lower right hand portion of the phase plot (pressure drop, Δ P, as a function of mass flow rate, Mc.) At t=0.75 sec the throttle area is abruptly reduced by a factor of 2. Immediately the compressor enters a surge condition, evidenced by the large, low frequency oscillations in Δ P and Mc and the attendant counterclockwise limit cycle in the phase plane. Comparison of the fuzzy set of the parameter residual with the prestored failure signatures identifies the condition as "abrupt surge" with a confidence level of 0.60. (A confidence level of zero corresponds to complete uncertainty and 1.0 to complete certainty.)

Clearly, this approach to turbomachinery instability characterization warrants additional study. It is anticipated that it will next be employed to characterize the

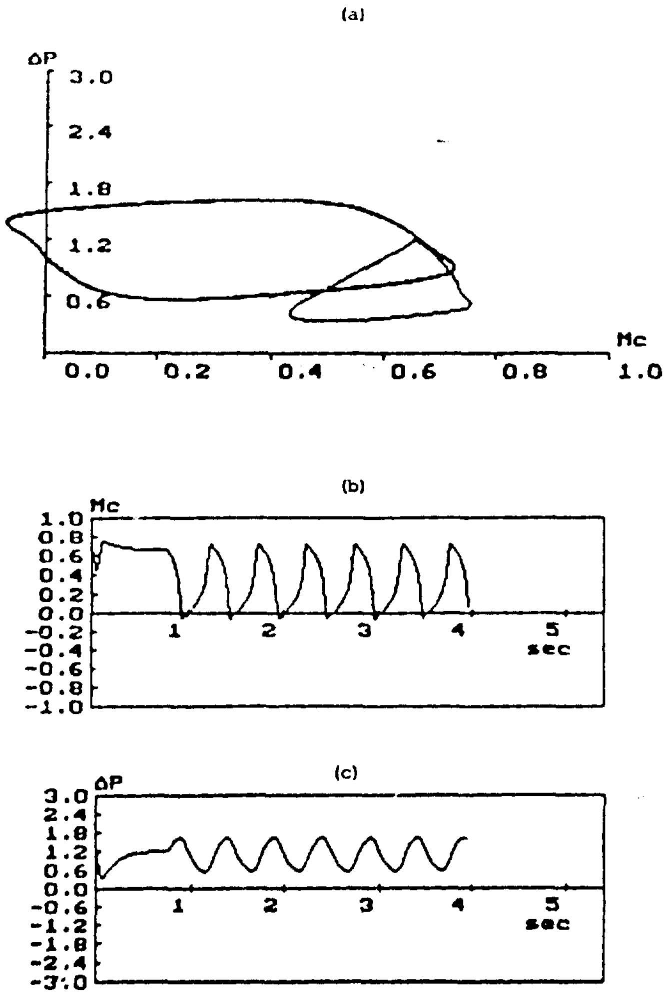

Figure 12: Detection of deep surge by the fuzzy logic methodology (a) phase plot of pressure drop, P vs. mass flow Mc; (b) corresponding time history of mass flow; (c) corresponding time history of pressure drop.

state of laboratory scale compressors in the ONR supported experiments in progress under the direction of Professor Nett at Georgia Tech.

CONCLUSIONS

As a result of the ONR program, it is now clear that active control is a viable approach for the improvement of performance of a range of complex physical systems and processes. Such commercially important examples as turbomachinery surge and stall control and combustion control are cases in point. As the program has proceeded the desirability of good physical models (simulators) has become progressively more evident, not only as a basis for specifying the initial plant model but also for choosing effective actuator types and locations and evaluating advanced feedback control strategies. Likewise, the potential utility of artificial intelligence-based fault detection, system identification and feedback control strategies has been established.

To fully exploit active control concepts in the design (or retrofit) of complex systems, additional work of a number of types is needed. Perhaps the most obvious is the conduct of experimental studies at progressively larger scales and in progressively more realistic environments. Such experiments serve several purposes. They quantify the effectiveness of active control at the larger scales. They provide the basis for testing and, if necessary, improving simulations of the physical systems and processes. They provide the environment in which actuator and sensor designs can be evaluated for effectiveness. (Actuators may in fact represent the single most difficult engineering problem in the application of active control concepts.) Finally, it is in the context of such experiments that the potential utility of the advanced control concepts described in this paper must be evaluated. For example, the hierarchy between local control of individual actuators and global control of the interaction between them, described in the electromagnetic radiation context in the present paper, may assume additional importance when the scale of the system and associated number of actuators and sensors increases.

A second area of continuing investigation should be the combined use of active and passive control methods. Experiments to date in laboratory scale combustion systems suggest that the two approaches can be used effectively in combination more satisfactorily than either one alone. It is plausible that the same will be true in other systems and processes, but the question has not yet been explored in detail.

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